Popular Summary

Pulsed lidars consist of a transmitter laser, a detector, and some optical components. A laser beam is fired from the transmitter; attenuates and backscatters as it travels and interacts with atmospheric molecules, aerosols and clouds in the sky; and then returns back to the detector. Because these signals come back with different strengths at different times, they can be used to retrieve vertical distributions of aerosol and cloud layers. While most existing instruments retrieve either aerosol or cloud properties, lidars can retrieve both but only for optically thin clouds. Up to now, we have been unaware of any single instruments that can retrieve optical depths for both aerosols and thick clouds.

Here we provide a proof-of-concept that optical depths for both aerosols and thick clouds can possibly be retrieved using a single lidar. When the lidar receives returned signals, it also unavoidably receives solar background light that is unwanted. Typically, solar background light is a noise and has to be removed. However, as with yard sales where one person's trash may be another person's treasure, one man's noise is another man's signal. The solar background light is the solar radiance coming from overhead. Using solar background light as a signal rather than a noise, we have found that lidars can retrieve optical depth of thick clouds.

Validations against other instruments show that retrieved cloud optical depths agree within 10–15% for both cases of overcast stratus and broken clouds. In fact, for broken cloud cases, one can retrieve not only the aerosol properties in clear-sky periods using lidar signals, but also the optical depth of thick clouds in cloudy periods using solar background signals. Because it is crucial to have simultaneous measurements of cloud and aerosol optical properties at the same location when studying the interactions between clouds and aerosols, lidar observations possess great untapped potential for such research.

Cloud optical depth retrievals from solar background "signal" of micropulse lidars

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Abstract

Pulsed lidars are commonly used to retrieve vertical distributions of cloud and aerosol layers. It is widely believed that lidar cloud retrievals (other than cloud base altitude) are limited to optically thin clouds. Here we demonstrate that lidars can retrieve optical depths of thick clouds using solar background light as a signal, rather than (as now) merely a noise to be subtracted. Validations against other instruments show that retrieved cloud optical depths agree within 10–15% for overcast stratus and broken clouds. In fact, for broken cloud situations one can retrieve not only the aerosol properties in clear-sky periods using lidar signals, but also the optical depth of thick clouds in cloudy periods using solar background signals. This indicates that, in general, it may be possible to retrieve both aerosol and cloud properties using a single lidar. Thus, lidar observations have great untapped potential to study interactions between clouds and aerosols.

I. INTRODUCTION

Micropulse lidar (MPL) systems, developed in 1992 (Spinhirne et al., 1995), are now widely used to retrieve heights of cloud layers and vertical distributions of aerosols layers (Welton et al., 2002; Matthais et al., 2004). MPL time-dependent returned signal is proportional to the amount of light backscattered by atmospheric molecules, aerosols and clouds. However, measured photon counts must be converted to attenuated backscatter profiles, and during the process a number of noise sources need to be subtracted (Campbell et al., 2002; Welton and Campbell, 2002). One source of noise is solar background light; its contribution remains significant even though the narrow field of view of MPL greatly limits the amount of solar radiation. Fortunately, this noise can be estimated from lidar returns beyond 30 km, which have no discernible backscatter.

One man's noise is another man's signal. The solar background noise is the solar zenith radiance, which can be used to retrieve cloud optical properties (Marshak et al., 2004; Chiu et al., 2006). We are unaware of any retrieval algorithm that uses the solar background light observed by lidars as a signal. This paper aims to address this issue by providing a proof-of-concept for using solar background "signal" from MPL to retrieve cloud optical depth. We will also evaluate results against those retrieved from other methods, and discuss the potential of our method to shed light on aerosol-cloud interactions.

II. APPROACH

Solar background signal is estimated from lidar bins beyond 30 km in units of photon counts. For retrieval purposes, photon counts must be converted to actual radiance. This conversion is instrument-dependent. Valencia et al. (2004) demonstrated that converted MPL solar background radiance agreed with zenith radiance that was calculated from principal plane measurements of a sunphotometer at the Goddard Space Flight Center (GSFC) site of AERONET (Aerosol Robotic Network; Holben et al., 1998). In this study we followed their method and derived calibration coefficients from the sunphotometer when its data are available.

Micropulse lidars of ARM (Atmospheric Radiation Measurement) Program and of NASA MPLNET (Micropulse Lidar Network; Welton et al., 2001) both operate at a 523 nm wavelength. The general relationship between zenith radiance and cloud optical depth at this wavelength is depicted in Fig. 1, based on 1D plane-parallel radiative transfer. Clearly, this relationship is not a one-to-one function. There are two cloud optical depths that give the same zenith radiance: one corresponds to thinner clouds and the other to thicker clouds. Thus, it is impossible to unambiguously retrieve cloud optical depth from solar background signal of a one-channel MPL. To remove this ambiguity, a criterion is needed to distinguish thick clouds from thin clouds or no clouds. A simple criterion adapted here assumes that if a lidar beam is completely attenuated, the detected clouds correspond to the larger optical depth.

Retrievals from MPL solar background signal are intercompared with those from other three instruments. The first instrument is the ARM MFRSR (multifilter rotating shadowband radiometer), which provides 20-second averages of both direct and diffuse solar flux in narrow bands centered at 415, 500, 615, 673, 870, and 940 nm. We used direct and diffuse transmittance at 415 nm, together with 1D radiative transfer theory, to retrieve cloud optical depth, similar to the method of *Min and Harrison* [1996].

The second instrument is the ARM 1NFOV (one-channel narrow field-of-view radiometer), which provides 1-second zenith radiance at 870 nm. Retrieval method from 1NFOV observations is same as that from MPL using the relationship shown in Fig. 1, but with different surface albedo and wavelength. Similar to MPL, additional information is needed to yield a final retrieval from those two possible optical depths. We used a transmittance threshold to discern cloud scenes (Dong et al., 1997; Turner et al., 2006). When MFRSR-calculated transmittance is greater (smaller) than the threshold, the detected clouds have a smaller (larger) optical depth. The threshold is given as the transmittance at the cloud optical depth τ^* that corresponds to the maximum radiance of the curve shown in Fig. 1. Note that the threshold is not a constant but depends on solar zenith angle.

The third instrument measures zenith radiance at two wavelengths (673 and 870 nm), including the ARM 2NFOV(two-channel narrow field-of-view radiometer) and AERONET CIMEL sunphotometers. 2NFOV provides 1-second measurements; CIMEL takes 10 measurements of zenith radiance with 9-second temporal resolution only when clouds block the sun (i.e., cloud mode). Retrieval method from dual-channel radiances is unambiguous over vegetated surfaces. It is based on the fact that in these two spectral regions, clouds have nearly identical optical properties while vegetated surfaces reflect quite differently. Details can be found in Marshak et al. (2004).

III. RETRIEVAL RESULTS

Retrievals from solar background signal of MPL, presented in this section, are compared with those from: 1) one-channel radiances and fluxes at the ARM Oklahoma site; 2) two-channel radiances in the ARM MArine Stratus Radiation Aerosol and Drizzle (MASRAD) field campaign at Point Reyes, California; and 3) sunphotometer measurements at the NASA/GSFC site.

a. Case 1: ARM Oklahoma site

Due to high frequency of and high climate sensitivity to thin clouds, ARM created a working group, CLOWD (Clouds with Low Optical Water Depth), to focus on microphysical properties of clouds with low liquid water paths (Turner et al., 2006). In their study, comparisons and evaluations of different remote sensing methods were performed. Among those retrieval methods, MPL was excluded because lidar measurements were supposed to work only for optical depths less than ~ 3. Beyond optical depth of 3, lidar returns are limited due to strong cloud attenuation. However, as

will be demonstrated next, using solar background signal we are able to overcome this limitation and retrieve larger cloud optical depths from MPL.

One of the CLOWD cases, a single-layer overcast warm cloud at the ARM Oklahoma site on March 14, 2000, is selected for illustration. Calibrations of MPL solar background signals were conducted against 6-month observations of AERONET CIMEL. Retrievals from MPL are compared with those from one-channel zenith radiances and fluxes, which were measured by 1NFOV and MFRSR.

Figures 2a–2d present the time series, histograms, and scatter plots of cloud optical depths retrieved from MPL, 1NFOV, and MFRSR. Retrievals from these three methods show similar temporal variations. The average cloud optical depth of MPL is 14, which is close to that retrieved from MFRSR. However, retrievals from MPL are generally 10–15% smaller than those from 1NFOV. This bias can be seen in Fig. 2c as well, which reveals a good linearity below the diagonal line between retrievals of MPL and 1NFOV. Due to a smaller sample size, the linearity between MPL and MFRSR retrievals is not clear in Fig. 2d.

b. Case 2: ARM Point Reyes field campaign

The MASRAD experiment was conducted at Point Reyes, California during May – September 2005. One of the scientific goals of this experiment was to understand the relationship between cloud microphysics/structures, drizzle and radiation in marine stratus clouds (Miller et al., 2005). Due to the locations of instruments, we compared our retrievals from MPL with those from zenith radiances measured by 2NFOV.

Note that sample volumes from 2NFOV and MPL are quite different. First, these two instruments have different fields of view (FOV). While 2NFOV has a FOV of 0.02 rad (1.1°), MPL has a FOV of only 100 μrad. Because of the extremely narrow FOV of MPL, the cloud situation for MPL is either clear-sky or overcast. As a result, MPL do not suffer from the clear-sky contamination problem when clear and cloudy pieces of sky are simultaneously observed (Chiu et al., 2006). Second, 2NFOV has a sampling resolution of 1 second, but MPL averages over 30 seconds in order to collect a sufficient amount of photons. To make a meaningful intercomparison between retrievals of MPL and 2NFOV, only overcast cases are compared here to reduce the uncertainty resulting from two different sample volumes.

Overcast cases were objectively selected as follows: when MFRSR-retrievals were found continuously greater than 5 for at least one hour, we defined the time period as overcast. An example overcast sky image is shown in Fig. 3a. Unlike the Case 1, we were unable to calibrate solar background signal of the MPL against CIMEL observations in this field experiment, because no CIMEL was deployed. Therefore, we first empirically derived the calibration coefficient by comparing retrievals from uncalibrated solar background signal with those from 2NFOV for only one overcast case. This coefficient was then applied to all other 110 overcast cases.

A scatter plot of cloud optical depths retrieved from MPL versus those from 2NFOV is shown in Fig. 3b. Surprisingly, even though we only used one case to derive the calibration coefficient, for all overcast cases the majority of retrieval pairs are close to the diagonal line, and optical depths agree within 10–15%. The difference in the average cloud optical depths of the two methods is only 1.

c. *Case 3: MPLNET*

Case 3 is based on measurements of the MPLNET at NASA/GSFC, Maryland. In contrast to previous cases, this was a broken cloud case. Because of the ambiguity of retrievals from only one channel, we manually separated thin from thick clouds. When the returned signal was not completely attenuated, it was assumed that clouds were thin.

We validated our retrievals against an AERONET CIMEL operated in "cloud mode" (Marshak et al., 2004). Figures 4a–4c show the time series of vertical backscatter profile of MPL, and corresponding retrievals from MPL and CIMEL. The mean cloud optical depths from MPL and CIMEL are 41 and 44, respectively, and their correlation is around 0.86. Except for a few outliers, errors of retrievals from MPL are again around 10–15% compared to those retrieved from CIMEL.

Note that the retrieval method from solar background signal is not problem-free (Fig. 5). As shown in Fig. 1, a given zenith radiance corresponds to two possible cloud optical depths. For some radiance, these two optical depths are quite different, and thus it is easy to remove the ambiguity using a 'returned' or 'no-returned' signal as described above. However, for some radiance, the two optical depths are not different enough to decide which one should be chosen (as demonstrated by the circle in Fig. 5). This ambiguity leads to difficulty in resolving cloud optical depths in the range approximately between 3 and 8. In other words, thin cloud optical depths (less than 3) can be obtained directly from the attenuated lidar signal. Thick cloud optical depths (greater than 8) can be retrieved with the method demonstrated here. Retrieval of intermediate optical depths would require new information, such as another lidar wavelength or additional instrumentation.

IV. CONCLUSIONS AND DISCUSSIONS

We proved that the solar background light, which is a noise to lidar applications and must be removed from lidar returns, can be used as a signal to retrieve cloud optical depth. This idea was tested for various cases, locations, and instruments. Compared to cloud optical depths retrieved from other methods, it is found that our retrievals generally agree within 10–15%. This promising result extends the retrieval ability of micropulse lidars to thicker clouds, and is no longer limited to detecting thin clouds only.

Due to the ability to retrieve vertical profiles of aerosol properties, lidar observations are also an essential element in the study of aerosol indirect effects (Diner et al, 2004b). However to better understand the effect of aerosols on clouds, it is crucial to have simultaneous measurements of cloud and aerosol optical properties at the same location.

Currently neither single ground-based instruments nor satellite sensors can provide such datasets. Here we showed that with broken cloud situations, one can retrieve not only aerosol properties during clear-sky periods via lidar signals, but also the optical depth of thick clouds during cloudy period via solar background lights. In other words, aerosol and cloud optical properties can be retrieved using the same instrument. This indicates that lidar observations have great potential to serve as a unique dataset allowing us to better understand how changes of aerosol in the environment impact cloud properties.

Acknowledgements

This research was supported by the Office of Science (BER), U.S. Department of Energy, Interagency Agreement No. DE-AI02-95ER61961, as part of the ARM program. MPLNET is funded by the NASA Earth Observing System and Radiation Sciences Program.

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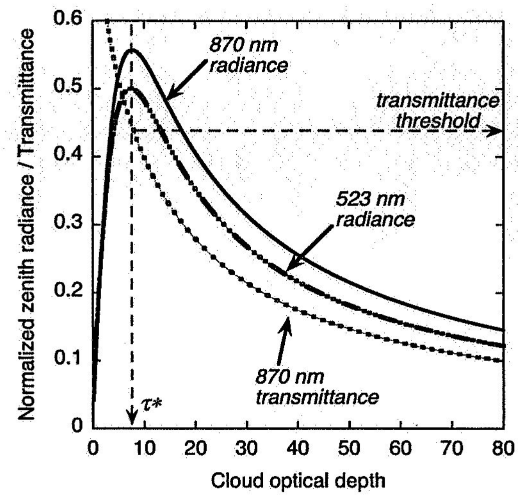

Fig. 1 Downward 523 and 870-nm radiance and transmittance vs. cloud optical depth calculated by the 1D radiative transfer model DISORT [*Stamnes et al.*, 1988] with a surface albedo of 0.05 and 0.35, respectively. Solar zenith angle is 60°. τ^* is the optical depth that corresponds to the maximum radiance and the transmittance threshold at 870-nm.

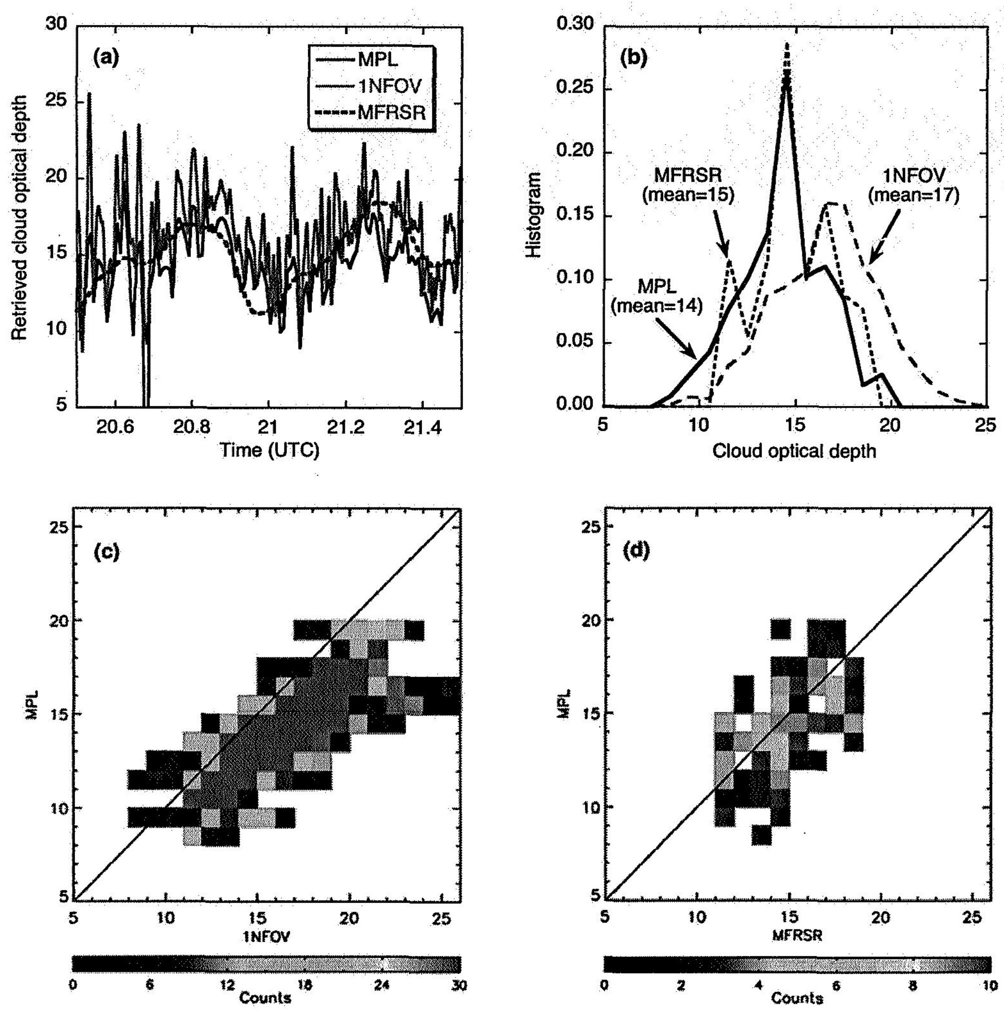

Fig. 2 Retrieved cloud optical depths for one of CLOWD case at the ARM Oklahoma site on March 14, 2000. (a) Time series; (b) histograms; (c) a scatter plot of retrievals from MPL vs. those from 1NFOV; and (d) same as (c), but for retrievals from MPL vs. those from MFRSR. Note that MPL, 1NFOV, and MFRSR provide measurements every 30, 1, and 20 seconds, respectively.

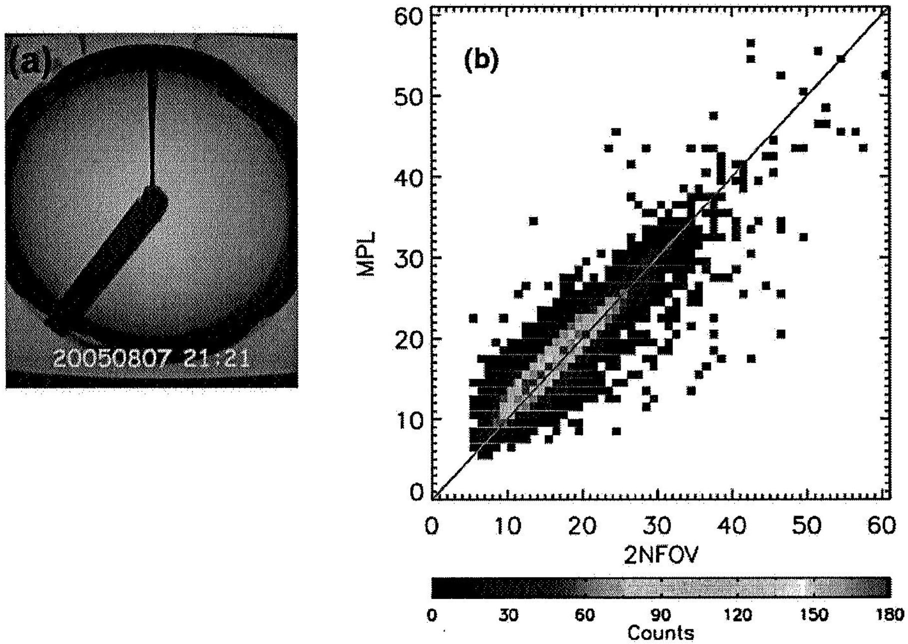

Fig. 3 (a) An example overcast sky image taken at the Point Reyes National Seashore, California during the ARM field campaign; (b) a scatter plot of retrieved cloud optical depths from MPL vs. those from 2NFOV for all overcast cases.

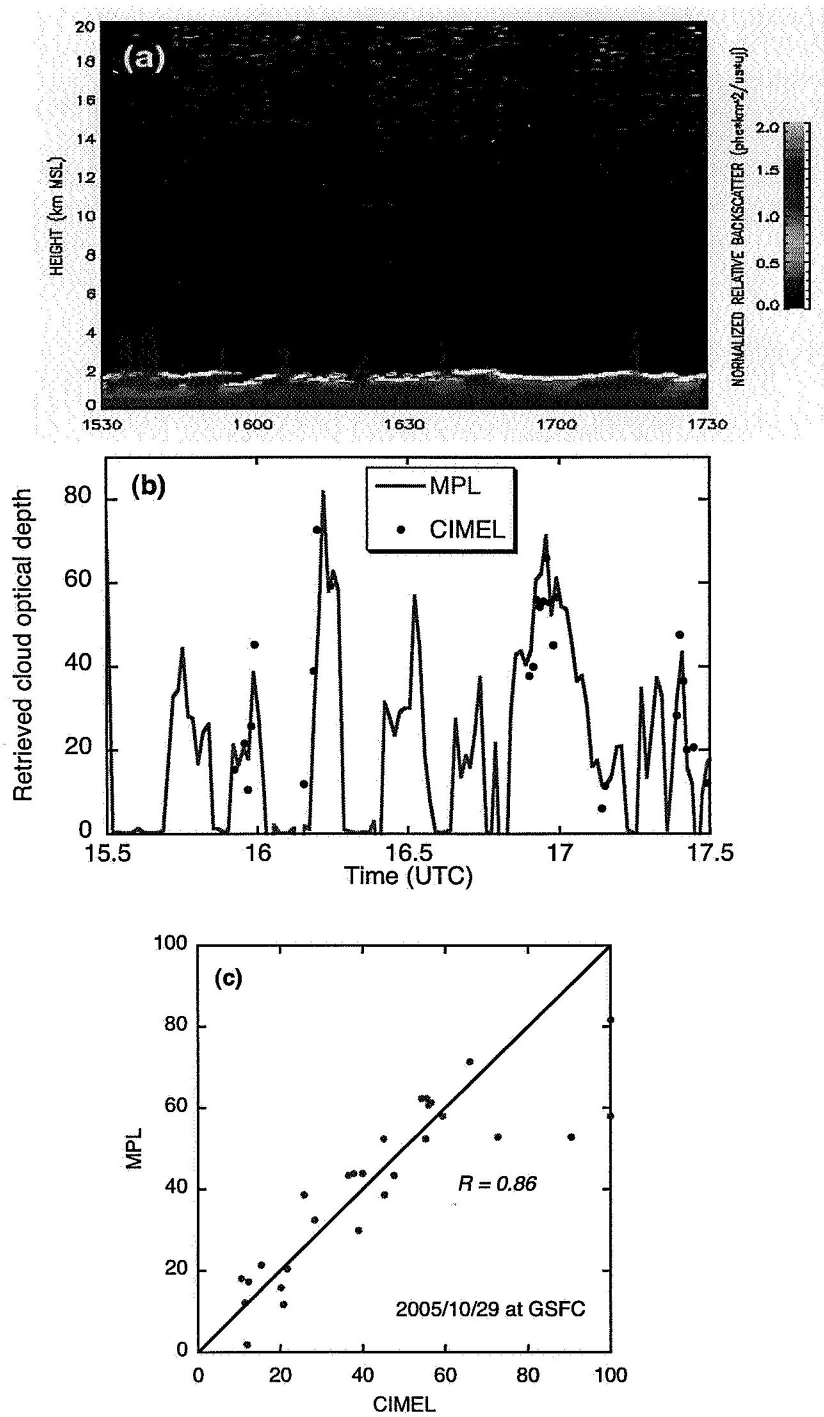

Fig. 4 (a) A time series of MPL backscatter vertical profile at GSFC on Oct. 29, 2005. More details can be found in http://mplnet.gsfc.nasa.gov, and http://climate.gsfc.nasa.gov/viewImage.php?id=161. (b) The time series and (c) a scatter plot of corresponding cloud optical depths retrieved from MPL and CIMEL are also shown here.

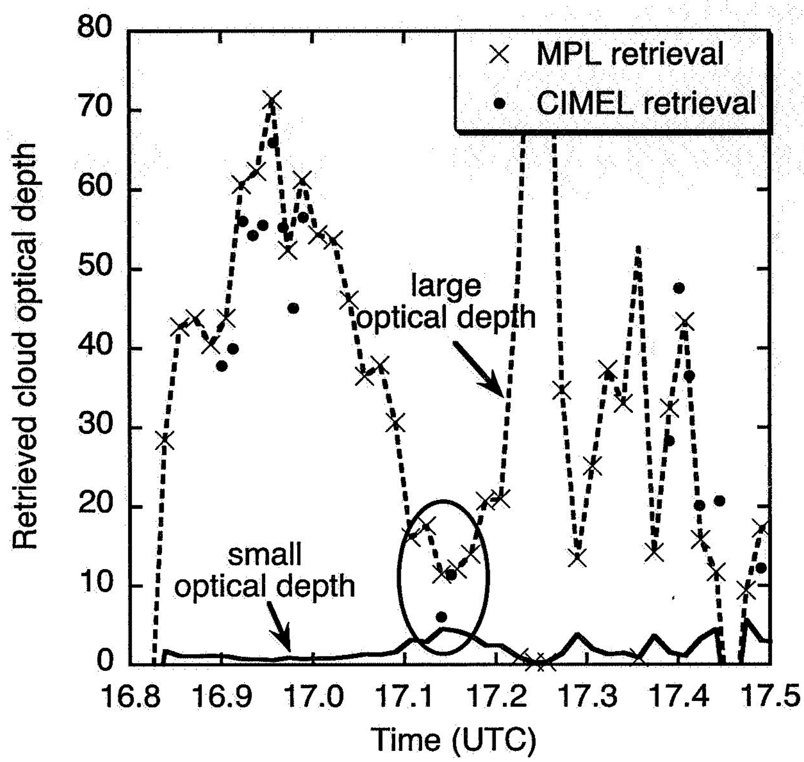

Fig. 5 Same as Fig. 4b, but co-plotted with two possible optical depths that correspond to the same zenith radiance.